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STUDY OF HEAT TRANSFER CHARACTERISTICS

OF HOT-GAS IGNITERS

Second Quarterly Progress Report for Period Ending
15 December 1966

J. A. Wrubel

Rocketdyne, a Division of North American Aviation, Inc.,
6633 Canoga Avenue, Canoga Park, California

TECHNICAL REPORT AFRPL-TR-66-358

December 1966

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Air Force Rocket Propulsion Laboratory
Research and Technology Division
Edwards, California
Air Force Systems Command
United States Air Force

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FOREWORD

This technical report presents the effort made during the second quarter of a contract entitled "Study of Heat Transfer Characteristics of Hot-Gas Igniters." The study was conducted by the Research Division of Rocketdyne, a Division of North American Aviation, Inc. The second quarter effort, conducted during the period 16 September to 15 December 1966, was authorized by the USAF Rocket Propulsion Laboratory under Contract AF04(611)-11613. The Air Force Project Monitor is 1/Lt. C. E. Payne, RPMC.

This report was submitted on 27 December 1966 as Rocketdyne Report No. R-6856-2.

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

This technical report has been reviewed and is approved.

Charles Cooke
Division Chief,
Solid Rocket Division

ABSTRACT

This program is concerned with determining the convective heat transfer characteristics of pyrogen igniters in both the aft-end and head-end configurations for three-pointed star and conocyl motor grains. Heat transfer modeling tests using thin-plate calorimetric techniques are being used to evaluate the heat transfer distributions. The second quarter effort reported herein was directed toward fabrication of the test sections for the model heat transfer experiments, procurement of the propellant grains for the demonstration motor test series, conducting of a majority of the tests for the experimental phase of the program, completion of the computer program changeover, and test data analysis.

CONTENTS

SUMMARY

During the second quarter of the "Study of the Heat Transfer Characteristics of Hot-Gas Igniters," major effort was directed toward fabrication of the test sections for the model heat transfer experiments, procurement of the propellant grains for the demonstration motor test series, the conducting of a majority of the tests for the experimental phase of the program, completion of the computer program changeover, and test data analysis.

The model heat transfer test sections consisted of star port and conocyl port grain configurations incorporating a rational charge of geometric variables, i.e., star point angle, cone angle, cone spacing, and cross-sectional area. Eight test sections, five star and three conocyl, were fabricated.

A subcontract was let to the United Technology Center for the loading of UTC 3001 solid propellant into Rocketdyne-supplied hardware. The eight demonstration motor cartridges will consist of three cylindrical port, four star port, and one solid port grain configurations.

The high gas temperature critical experiment and Schlieren test series have been concluded. The model heat transfer experiments are nearly two-thirds completed with 57 of a planned 90 tests accomplished to date. The computer program changeover was finished with the successful run of a trial case and is now ready for the processing of the data from the model heat transfer experiments.

Test data analysis has been completed for the high gas temperature critical experiment and Schlieren tests. The critical experiment demonstrated that the heat transfer coefficient remained constant as a function of time when a high driving temperature potential was present. A letter was sent to those named on the final report distribution list of Contract AF04(611)-9884, alerting them to this significant result. A general qualitative analysis of the Schlieren tests which establishes the flow field created

by head-end and aft-end, hot-gas igniters is given in the data analysis section of the body of this report. The raw data from the model heat transfer experiments is being prepared for machine computation.

Completion of the model heat transfer experiments will be accomplished at the beginning of the third quarter. Demonstration motor buildup will be initiated, and a major portion of the test data analysis will be conducted during this period. The testing program will maintain the orderly testing schedule established during the first quarter. Deviation from this schedule will be made if results suggest a change in parametric emphasis.

INTRODUCTION

A 12-month program entitled "Study of Heat Transfer Characteristics of Hot-Gas Igniters," was initiated by the Rocketdyne Research Division under Contract AF04(611)-11613 on 16 June 1966. The objective of this study is to develop relationships which predict convective heat transfer from a hot-gas igniter to a solid propellant grain and to demonstrate that such relationships permit a quantitative prediction of the ignition delay. These relationships, based on a comprehensive testing program, will be derived for typical head-end and aft-end, hot-gas igniters for practical solid propellant grain designs, i.e., stars and conocyls. The testing program consists of: (1) a critical test to investigate a transient boundary layer mechanism, (2) Schlieren tests to gain fundamental understanding of the interaction of fluid dynamics upon the heat transfer of hot-gas igniters, (3) model heat transfer tests to determine the influence of geometric changes of solid propellant grain ports and position of the igniter nozzle on the heat transfer to the propellant surface, and (4) demonstration motor firings to determine the applicability of the developed relations to an actual propellant system.

Frequently, solid propellant rocket motors are ignited by hot-gas sources such as smaller burning solid propellant charges (pyrogen igniters) or pyrotechnic grains which exhaust their combustion products into the main combustion chamber through convergent or convergent-divergent nozzles located in either the head-end or aft-end of the motor. Historically, the design of hot-gas igniters evolved from empirical "rules-of-thumb" developed by motor manufacturers based upon massive testing programs involving many different motor systems. Current refinements to available "rules-of-thumb" still make hot-gas igniter design more costly than would be necessary if generalized design principles were available. Realizing that the preignition period in hot-gas ignition largely involves a convective heat transfer process, a program under Contract AF04(611)-9884, entitled "A Study of the Heat Transfer Characteristics of Hot-Gas Ignition," (Ref. 1)

was conducted. This program developed generalized correlations and analysis procedures on a substantial theoretical and experimental basis that could define particular simple hot-gas ignition system requirements. The use of modeling techniques facilitated the gathering of pertinent information in a rapid and inexpensive manner.

Current ignition research programs are making significant progress toward the elevation of ignition system design from an art to a science. Relationships correlating heat flux, pressure, and ignition delay have been developed for some rubber-base propellants under Contract AF04(611)-9701, entitled "Ignition of Solid Propellant Under Vacuum," (Ref. 2). Of fundamental importance in the practical utilization of the foregoing information is knowledge of the characteristics and mechanisms of the heat delivery from the igniter gas to the propellant surface which was developed for cylindrical geometry in Ref. 1. The extension of the previously developed modeling techniques and procedures to more complex geometries (i.e., star and conocyl configurations), coupled with the data for a particular propellant from Ref. 2, should allow, for the first time, the scientific tailoring of an igniter to a specific solid propellant motor without recourse to empirical rules.

During the first quarter effort on the Study of Heat Transfer Characteristics of Hot-Gas Igniters (Ref. 3), major effort was directed toward reactivation of the hot-gas heater, design of test section components, procurement of materials, hardware fabrication, the computer program changeover, and test planning. Reactivation of the hot-gas heater eliminated the annoying problem of oxide deposition on test section hardware, allowed far more rapid changeover of test section thermocouple instrumentation, and increased the response rate of the gaseous nitrogen pressure regulator. Test stand modifications were completed, and the checkout of the apparatus and design approaches was successful. All test section designs were finished. Fabrication was completed for: components for the critical experiment, components for the Schlieren test, the optimum expansion ratio model igniter nozzles, and components for long-lead-time items for the demonstration motor firings. A tentative test matrix that included a total of 115 tests was formulated.

In the work of the second quarter, described in detail in this report, the following tasks were accomplished: fabrication of the star port and conocyl port test sections, initiation of procurement of the demonstration motor propellant grains, completion of the testing and data analysis for the high gas temperature critical experiment and the Schlieren test series, the conducting of approximately two-thirds of the planned model heat transfer tests, and final checkout of the improved computer program for test data reduction of the model heat transfer experiments.

EXPERIMENTAL EQUIPMENT

A complete description of the hot gaseous nitrogen supply system and associated subsystems, located in Pit 2 of the Combustion and Heat Transfer Laboratory, Santa Susana Field Laboratory, is contained in AFRPL 65-158, the final report of Contract AF04(611)-9884. This test facility and applicable test section hardware fabricated previously are being used in the current program and, since their description has been given previously, only modifications to the existing apparatus and newly designed equipment will be reported.

During the second quarter, five star port and three conocyl port model heat transfer test sections and a test section for jet interaction studies were fabricated. This completed the test section fabrication 1 month ahead of schedule. Also, propellant grains for the demonstration motor firings were ordered.

The jet interaction studies test section was designed to permit the use of Schlieren photography. The test section consisted of a 2.11-inch-wide two-dimensional, pyrex glass-windowed exhaust nozzle. The two-dimensional nozzle contour matched the area ratio of the one-dimensional, 4-inch-diameter, 3-to-1 port area to throat area exhaust nozzle fabricated under Contract AF04(611)-9834. The contour was generated by matching the area ratio at each 0.30-inch axial station referenced from the nozzle inlet.

Five test sections in a three-pointed star pattern were constructed from 0.020-inch stainless-steel sheets. The three pointed star pattern was provided by laterally clamping the edges of three preformed sheets with carbon steel strips that were nine-tenths of the test section length.

The sheet metal star was soft-soldered to 1/4-inch brass flanges that were cut to the star shape. The geometric properties of the five test sections were:

a. One-inch-diameter equivalent flow area, 30-degree included star ray angle, 5.49-inch length, and 2.12-inch star outside diameter

b. Two-inch-diameter equivalent flow area, 10-degree included star ray angle, 6.19-inch length, and 7.10-inch star outside diameter

c. Two-inch-diameter equivalent flow area, 20-degree included star ray angle, 8.98-inch length, and 5.16-inch star outside diameter

d. Two-inch-diameter equivalent flow area, 30-degree included star ray angle, 10.98-inch length, and 4.24-inch star outside diameter

e. Four-inch-diameter equivalent flow area, 30-degree included star ray angle, 22.2-inch length, and 8.52-inch star outside diameter

Test section (a) was instrumented with 25, 5-mil chromel-alumel thermocouples fastened in three rows along one side of one star ray. The first row (top) was located 1/4 inch below the lateral clamp and thermocouple spacing was 1 inch. The next row bisected the slant height between the first row and the star peak (the point closest to the star axis which is also the location of the third row). Thermocouple spacing was 1/2 inch. All rows began 1/2 inch from the inlet side of the test section. Instrumentation was attached to the remaining four test sections in a similar manner. The thermocouple disposition was as follows:

1. Section (b)—27 thermocouples with spacing of 1 inch for the first row, 1/2 inch for the second and third rows, with the exception of the last thermocouple in the second row which was 1 inch from the preceding thermocouple.

2. Section (c)—27 thermocouples with a spacing of 1 inch for all three rows

3. Section (d)—33 thermocouples with a spacing of 1 inch for all three rows

4. Section (e)—45 thermocouples with a spacing of 1 inch for the first 10 thermocouples, 2 inches for the next four, and 4 inches for the last thermocouple for all three rows

To allow attachment of the exhaust nozzles to the star port test sections and to create a smooth flow transition from the star-shaped flow area into the conical exhaust nozzle, a plenum and a conical flow area reducing section was added to the test section. Five plenum chambers are fabricated from 3/8-inch aluminum plate, one for each test section, with the inside diameters corresponding to the test section outside diameter. Three conical flow area reducing sections were fabricated from 5/8-inch aluminum plate. The reducing section consisted of a 45-degree chamfer from the minimum inside diameter that corresponds to the exhaust nozzle inlet diameters of 1, 2, and 4 inches. The exhaust nozzle was bolted to the reducing section and the reducing section and plenum chamber was bolted to the downstream star port test section end flange to complete a test section assembly.

The star port test sections were demonstrated to be structurally unstable during prototype testing; therefore, they require structural support. The required support was produced by filling the exterior star valleys with casting plaster.

The procedure used for preparation of the test sections for testing was:

1. Apply fiberglass tape over the thermocouple junctions but incorporate an air gap between the tape and the junction.
2. Fill the exterior of the star valleys with casting plaster.
3. Place wood bearing plates on top of the plaster surface.
4. Attach large hose clamps to the bearing plates.

This procedure ensures that the structural supports remain in place and permits experimentation at higher test section pressures because of the greater rigidity of these sections.

The ability to monitor the gas temperature near the star and conocyl test section inlets is a prerequisite to meaningful heat transfer results. A temperature drop exists between the hot-gas valve and the injector nozzle inlet that must be determined experimentally. To accomplish this, a 0.042-inch, Inconel-sheathed, 5-mil thermocouple was installed 2 inches aft of the hot-gas valve and a three-pronged gas temperature probe consisting of three 0.042-inch, Inconel-sheathed, 5-mil thermocouples encased in 1/8-inch tubing was installed so that the junctions were located at the injector nozzle inlet. This allows measurement of the temperature drop in addition to accurate determination of the gas temperature. Since the injector nozzle location changes from run to run, depending on the test conditions, a number of sets of probes were constructed so that the probe was never more than 1/2 diameter from the injector inlet. These probes were held in place rigidly by a centering spider that slipped over the 1/8-inch, stainless-steel tubing.

Three test sections containing a conocyl section were constructed from 0.020-inch stainless steel. The cylindrical sections utilized seamless tubing and the truncated right circular cones were made from 0.020-inch-thick sheet stock. After the cones were formed and the lapped seams were silver soldered, the cone bases were silver soldered to ring flanges. Smaller ring flanges were silver soldered to one end of the cylindrical inlet and exit, to the conocyl section, and to both ends of the extension tubes.

The extension tubes fulfilled an overall length-to-diameter requirement of 10 for all three test sections. Next, the inlet tube was placed on the inside of one cone, and the exit tube was placed atop the other cone pair and both were silver soldered in place. Ring spacers were fabricated to allow variation of the cone gap. The assembly of the test section consisted of applying liquid Teflon to the selected ring spacer, placing the spacer between the inlet and exit cone sections, bolting the conocyl

section together, and attaching the extension tube to the exit end of the conocyl section. The geometric properties of the three sections were:

1. Two-inch-diameter, 30-degree conocyl section; 1/4- and 3/4-inch cone gap; 5-inch inlet and 3-inch exit
2. Two-inch-diameter, 60-degree conocyl section; 3/4-inch cone gap, 3-inch inlet; and 3-inch exit
3. Four-inch-diameter, 30-degree conocyl section; 3/4- and 1-3/4-inch cone gap; 6-inch inlet and 6-inch exit

The test sections were instrumented with 5-mil chromel-alumel thermocouples fastened in one row traversing the test section length. Thermocouple spacing was 1 inch on all conocyl section inlet and exit tubes except at the cylinder-cone interface where the thermocouples were placed 1/4 inch from the joint to minimize conduction errors. Thermocouple spacing was 1/2 inch on the cones starting 1/4 inch from the cylinder-cone interface, 1 inch on the 2-inch-diameter extension tubes, and 2 inches on the 4-inch-diameter extension tubes. The number of thermocouples mounted on conocyl test sections (1), (2), and (3) was 35, 35, and 41, respectively.

A buckling failure occurred during model heat transfer testing of the 60-degree, 2-inch-diameter conocyl test section. Consequently, structural support, made of casting plaster, was added to the external pressure-loaded cone. This support was made in a manner similar to that for the star port test sections.

Demonstration motor propellant grain manufacture will be accomplished in the next quarter. Liaison has been established with United Technology Center (UTC), and final contract arrangements have been made for the loading of UTC 3001 solid propellant into Rocketdyne-supplied hardware. The eight demonstration motor cartridges will consist of three cylindrical port, four star port, and one solid port grain configurations. The casting fixture components were shipped to UTC near the end of the quarter. Manufacture is scheduled to take place in conjunction with an existing UTC production contract to reduce costs.

EXPERIMENTAL OPERATIONS

During the second quarter, the high gas temperature critical experiment and the Schlieren test series were completed, jet interaction studies were performed, and nearly two-thirds of the model heat transfer tests were accomplished.

The high gas temperature critical experiment was completed early in the quarter. Upon initiation of testing, developmental problems with the pyrogen igniter became apparent. The igniter was overpressurizing and ejecting the exhaust nozzle. The cause was traced to an excessive booster charge, inhibiter failure, and pocket burning on the solid propellant surface. The igniter propellant charge was redesigned to reduce the amount of inhibition and booster charge required. Three successful checkout tests of the redesigned propellant charge confirmed the design changes. The critical experiments were run again, successfully, with igniter flowrates and durations of 1/2 lb/sec for 1/4 second, 1/2 lb/sec for 1/2 second, and 1/4 lb/sec for 2 seconds.

The Schlieren test series, which consisted of 14 tests, was completed 1 month ahead of schedule. Testing was conducted as outlined in the first quarterly report, with the addition of two duplicate tests where there was a possibility of a malfunction with the cinematographic Schlieren apparatus. The test series was designed to gain information about the flow fields produced by a sonic and supersonic injector nozzle operating in both the aft-end and head-end, hot-gas igniter orientations. A well-defined description of the flow field helps to clarify the heat transfer mechanism or mechanisms. The small number of tests did not allow complete quantitative description, but they provide results that are adequate for a qualitative description of the flow fields.

Jet interaction studies utilizing the two-dimensional pyrex glass-windowed exhaust nozzle were conducted in conjunction with the above Schlieren tests. Two tests were conducted with the supersonic injector nozzle operating at

a flowrate of 1 lb/sec, oriented in the aft-end igniter configuration. The only physical changes between the two tests was injector location in the exhaust nozzle throat. The locations were at the exhaust nozzle throat and exit, which corresponds to an ϵ^* of 0.8 and 2, respectively.

ϵ^* is defined as the ratio of the minimum annular area between the exit plane of an aft-end igniter exit cone and exit cone of the motor divided by the exhaust nozzle throat area. Some details of the interaction phenomena were obscured by the hardware. Further studies will be made to obtain this information at the end of the scheduled testing program if time and money permit.

Heat transfer model testing was initiated ahead of schedule and is proceeding at a faster rate than anticipated. It is expected that testing will be completed during the first month of the third quarter. Progress to the end of this quarter includes completion of testing for the head-end configuration and initiation of testing for the aft-end configuration. The planned total of 35 head-end tests utilizing star port and conocyl port test sections was accomplished. Two of a planned total of 35 tests of the aft-end igniter configuration have been completed. Some difficulty was encountered during testing in maintaining the integrity of the star port test sections. It was noted after the first few tests that the end flanges would loosen, the cause being the low-amplitude vibration produced by the test stand which fatigued the soft solder. This problem was solved with a minimum of rework by clamping the star test sections to the heater. This problem did not appear with the conocyl port test sections which were silver soldered at all joints.

DATA ANALYSIS

During the second quarter, the computer program changeover, data reduction for the high gas temperature critical experiment, and data reduction for the Schlieren tests and jet interaction studies were completed. Data reduction for the model heat transfer experiments was initiated.

The computer program changeover and incorporation of the improvements to the old program were completed. The new program was coded in Fortran H for use with the new IBM system 360 computer recently installed at Rocketdyne. Debugging has been completed and the program has successfully run a trial case. The program is now ready for use in processing the data for the model heat transfer tests. It is the final program used in the data reduction chain discussed below.

The hot-gas ignition model heat transfer test series utilizes the Beckman 210 transient data acquisition system and the IBM system 360 Model 40/65 digital computer for data reduction.

The recording of temperature data from the thermocouple-instrumented test sections is done on the Beckman 210. Millivolt signals received from the thermocouples are digitized into "Beckman counts" and recorded on magnetic tape. The digital signals are also converted back to analog through a Digital-Analog Converter (DAC), and recorded on brush recording paper rolls along with the digital time base. The analog data are used for quick visual reference and to supplement the reduction of digital data by aiding the selection of favorable time slices.

The IBM S/360 is utilized to reduce the digital data. The data from selected time slices are converted from "Beckman counts" to temperature units via fifth order calibrated polynomial expressions. The temperature and time data then enter the final reduction program (HOTGAS computer program). The HOTGAS program calculates gas-side temperatures, heat fluxes, and heat transfer coefficients. The printed output is in tabulated form, columnarized

with respect to time, and grouped according to thermocouple. The program contains many options for plotting the calculated data and the ability for storing these data on magnetic tape.

The data reduction for the high gas temperature critical experiment was completed. The heat transfer data and the pyrogen igniter performance parameters were tabulated to match the igniter operation to the heat transfer results. The only correction that was applied to the data was allowing for changes in mass flowrate. This resulted in the demonstration that the heat transfer coefficient is a constant as a function of time when a high driving temperature potential is present. Data scatter was within ±10 percent and might possibly be suppressed with a more complete analysis of the results.

The above tests proved that the postulated transient boundary layer mechanism for explanation of the transient heat transfer coefficient observed with the heat transfer tests conducted under AF04(611)-9884 is correct. Therefore, the correct time value for the derived correlations is zero time, and correlations for times greater than zero should not be used. An informal letter was sent to the recipients of the final report of Contract AF04(611)-9884, relating the results discussed above.

Data reduction of the Schlieren tests and jet interaction studies was completed. The review of the motion pictures yielded the following general qualitative observations:

1. Normal shocks exist downstream of the sonic igniter nozzle.
2. The initial pressurization in aft-end ignition is accomplished by a traveling normal shock wave.
3. Turbulence scales in both aft-end and head-end cases appear large but change as a function of flowrate and nozzle type.
4. High-density eddies are predominant outside the jet boundary and appear to be shed from this interface.

5. The jet boundary pulsates with time, but the shock locations are relatively constant.

6. Jet disintegration takes place in a shorter distance with a sonic injector nozzle than with a supersonic nozzle.

7. The flow in the exhaust nozzle is highly turbulent with turbulence pockets being of very small size.

8. In the exhaust nozzle, the jet boundaries are less proncunced in the aft-end case than those observed for the head-end tests.

9. Moving the injector toward the exhaust nozzle throat produces a similar shock pattern but compresses the jet boundaries.

Quantitative analysis of the motion pictures will be accomplished as required by the continuing fluid dynamic analysis. A more detailed description of the observations made from the Schlieren motion pictures will be given in the final report. Reproductions of individual frames from the Schlieren movies will be made during the next quarter for inclusion in the final report.

Data reduction has been initiated for the model heat transfer experiments. The output from the oscillographs and Brown recorders has been organized, and tabulations of pertinent data are being prepared. The thermocouple output data that has been stored on magnetic tape are being prepared for machine computation. The processing of the thermocouple data will take place early in the next quarter.

ANALYTICAL STUDIES

The head-end and aft-end fluid dynamic studies are continuing. The results of the jet interaction studies were given above in items 7, 8, and 9 of the Schlieren results. The results did not substantiate or disprove the results of the analysis made by Plumley (Ref. 4). Difficulty with the test setup reduced the amount of information that could be gathered from the Schlieren motion pictures. These tests will be rerun, if funding permits, in a redesigned test section. In addition, the Schlieren knife edge will be changed to accentuate horizontal density gradients to better observe boundary layer growth changes at the exhaust nozzle throat contour.

During the second quarter, reference literature was gathered and literature surveys were initiated. The technical papers will be reviewed during the third quarter while more information is being gathered.

EXPERIMENTAL PLANS

The testing program is currently 2 months ahead of schedule. The model heat transfer experiments will be completed in the first part of the third quarter. Major effort during the third quarter will be directed toward data analysis of the model heat transfer experiments and buildup for the demonstration motor firings. Demonstration motor testing is planned for the fourth quarter.

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13 ABSTRACT

This program is concerned with determining the convective heat transfer characteristics of pyrogen igniters in both the aft-end and head-end configurations for three-pointed star and conocyl motor grains. Heat transfer modeling tests using thin-plate calorimetric techniques are being used to evaluate the heat transfer distributions. The second quarter effort reported herein was directed toward fabrication of the test sections for the model heat transfer experiments, procurement of the propellant grains for the demonstration motor test series, conducting of a majority of the tests for the experimental phase of the program, completion of the computer program changeover, and test data analysis.

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